(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
17 April 2003 (17.04.2003)

PCT

(10) International Publication Number
WO 03/032666 A1

(51) International Patent Classification[7]: H04Q 7/32, H04B 7/26

(21) International Application Number: PCT/US02/31745

(22) International Filing Date: 4 October 2002 (04.10.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/974,587 9 October 2001 (09.10.2001) US

(71) Applicant: INTEL CORPORATION [US/US]; 2200 Mission College Boulevard, Santa Clara, CA 95052 (US).

(72) Inventor: SILVESTER, Kelan; 19840 NW Metolius Drive, Portland, OR 97229 (US).

(74) Agents: TROP, Timothy, N.; Trop, Pruner & Hu, P.C., Suite 100, 8554 Katy Freeway, Houston, TX 77024 et al. (US).

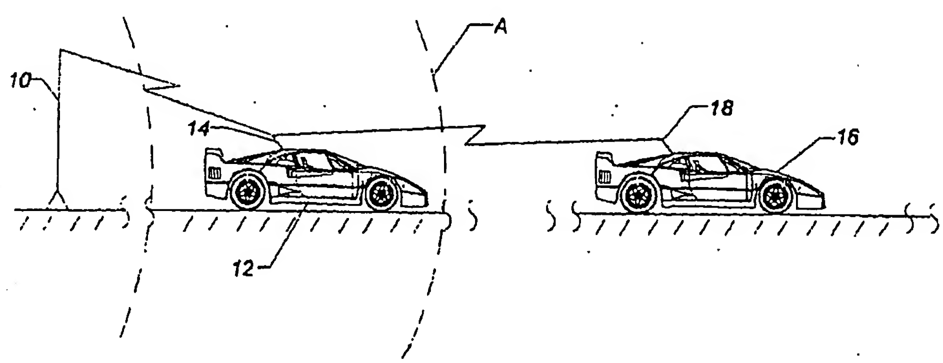
(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: MOBILE SIGNAL RELAY FOR CELLULAR TRANSMISSION IN REMOTE AREAS



(57) Abstract: A large number of vehicles (12) may be equipped with cellular repeaters (20). These repeaters (20) may receive signals from proximate towers (10) or proximate vehicles (16) and forward them on in order to complete communications that would not otherwise be possible. Thus, vehicles (16) that are attempting to make or receive cellular transmissions may have those transmissions completed via a mobile repeater in other vehicles (12). As a result, the range of existing cellular telephone systems may be extended without the need for an increased number of cellular towers.

WO 03/032666 A1

Mobile Signal Relay For Cellular Transmission In Remote Areas

Background

This invention relates generally to cellular communication systems and, particularly, to the use of cellular repeaters.

In a number of circumstances, cellular telephone users are frustrated by the lack of cellular telephone service. For example, when traveling along highways, the user may experience dropped calls because the user moves out of range of a sufficiently proximate cellular tower. In addition, in so-called pocket areas, users may experience the absence of cellular service because buildings or other geographical obstacles, such as mountains or valleys, mask communications with proximate towers.

Of course, one obvious solution is to increase the number of cellular towers. However, this approach comes with a number of disadvantages. The cellular towers and their maintenance may be expensive. In addition, many communities object to the presence of what are considered to be unsightly cellular towers.

Thus, it would be desirable to extend cellular service without increasing the number of cellular towers.

Brief Description of the Drawings

Figure 1 is a schematic depiction of one embodiment of the present invention; and

Figure 2 is a block diagram in accordance with one embodiment of the present invention.

Detailed Description

Referring to Figure 1, a cellular user traveling in an automobile 16 may attempt to place a cellular phone call. However, in the illustrated example, the vehicle 16 is too far from the most proximate cellular tower 10 to establish communications. However, an intermediate vehicle 12, including a cellular repeater coupled to an antenna 14, is available. Thus, the outgoing transmission from the vehicle 16 may be received by the vehicle 12 and automatically retransmitted to the tower 10. Because the vehicle 12 is in range of the tower 10, the cellular call may be completed. The operator of the vehicle 12 may have no idea that his vehicle and its repeater is being used to forward a telephone call

and may have no knowledge or access to the communication between the vehicle 16 and the tower 10.

If a large number of vehicles traveling on roads and highways are equipped with cellular repeaters, the range of existing cellular telephone systems may be extended. This may be accomplished without the need to increase the number of cellular towers. In effect then, each such vehicle becomes a mobile repeater. Whenever a repeater equipped vehicle happens to be in range of another vehicle that is not in range of any cellular tower, the repeater equipped vehicle acts to automatically forward incoming or outgoing communications. If the population of such repeaters is sufficient, the range of existing cellular phone systems may be greatly extended. Embodiments of the present invention may be applied in cellular telephone systems including those using Advanced Mobile Phone Service (AMPS), Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA), and Global System for Mobile Communications (GSM), as examples.

Cellular repeaters with relatively reasonable range may be made in sufficiently small form factors to be accommodated within passenger vehicles. Larger repeaters may be provided on large trucks that may extend the cellular system's range to an even greater degree. In some embodiments, the cellular repeaters may use existing radio technology in vehicles, such as existing AM/FM radios. In other words, the repeater may be incorporated with the existing automotive radio and may share components of such a radio.

Advantageously, the repeater does no signal processing so there is no way for cellular transmissions to be distorted, modified, recorded, intercepted, or the like. Thus, the repeater is advantageously simply a signal repeater.

Referring to Figure 2, a cellular repeater may include a pair of antennas 14a and 14b. Advantageously, the antennas 14a and 14b may be well isolated from one another. The antenna 14a may receive signals that are passed through the duplexer 22a, the isolator 24b, and an amplifier 26b, and then passed out through the duplexer 22b and through the antenna 14b. Similarly, incoming signals received by the antenna 14 may be passed through the isolator 24a and amplifier 26a before proceeding outwardly through the antenna 14a via the duplexer 22a. The isolators 24a and 24b may provide filtering in some embodiments. The isolators 22 and the amplifiers 26 may be coupled, as indicated, to the vehicle's existing battery power supply.

While the present invention has been described with respect to a limited number of embodiments, those skilled in the art will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover all such modifications and variations as fall within the true spirit and scope of this present invention.

What is claimed is:

1. A method comprising:
providing cellular repeaters in a plurality of vehicles; and
enabling those repeaters to receive cellular transmissions and to forward those transmissions between mobile users and proximate cellular towers.

2. The method of claim 1 including incorporating a cellular repeater into a vehicle radio.

3. The method of claim 1 including preventing the operator of a vehicle including a cellular repeater from intercepting a transmission to be forwarded.

4. The method of claim 1 including powering the repeater from a vehicle power supply.

5. The method of claim 1 including bi-directionally transmitting transmissions to and from cellular towers through said repeaters.

6. The method of claim 1 including bi-directionally transmitting transmissions to and from other mobile repeaters.

7. A cellular repeater comprising:
an antenna to receive or transmit a cellular signal;
an amplifier to amplify the cellular signal; and
a connection to a vehicular power supply.

8. The repeater of claim 7 including a pair of antennas.

9. The repeater of claim 7 including a pair of antennas, each of said antennas connected to a duplexer.

10. The repeater of claim 9 including a pair of amplifiers, each coupled to amplify a signal for one of said antennas.

11. The repeater of claim 7 including a pair of isolators, each isolator associated with one of said amplifiers.

12. A method comprising:
installing a repeater in a plurality of vehicles;
coupling the repeater to an automotive electrical system; and
enabling the repeaters to receive and transmit cellular communications and to forward those communications to proximate cellular towers.

13. The method of claim 12 including incorporating a cellular repeater into a vehicle radio.

14. The method of claim 12 including preventing the operator of a vehicle including a cellular repeater from intercepting a transmission to be forwarded.

15. The method of claim 12 including powering the repeater from a vehicle power supply.

16. The method of claim 12 including bi-directionally transmitting transmissions to and from cellular towers through said repeaters.

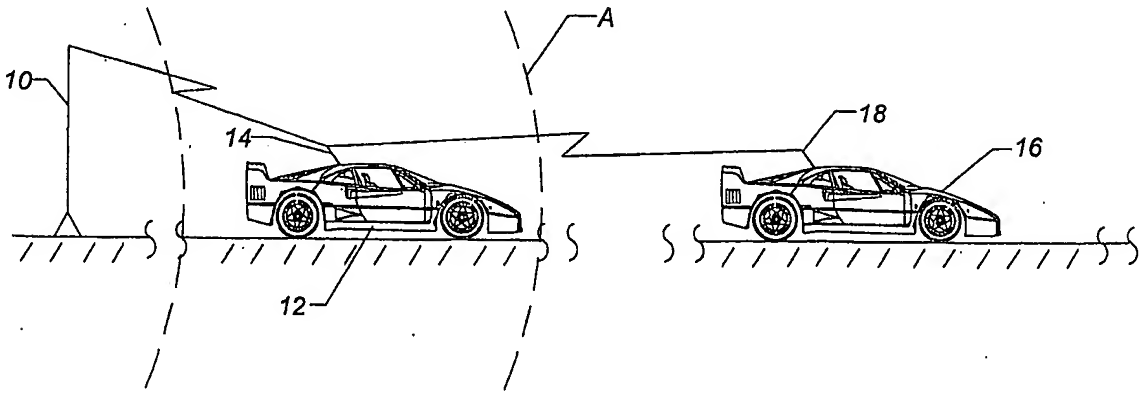


FIG. 1

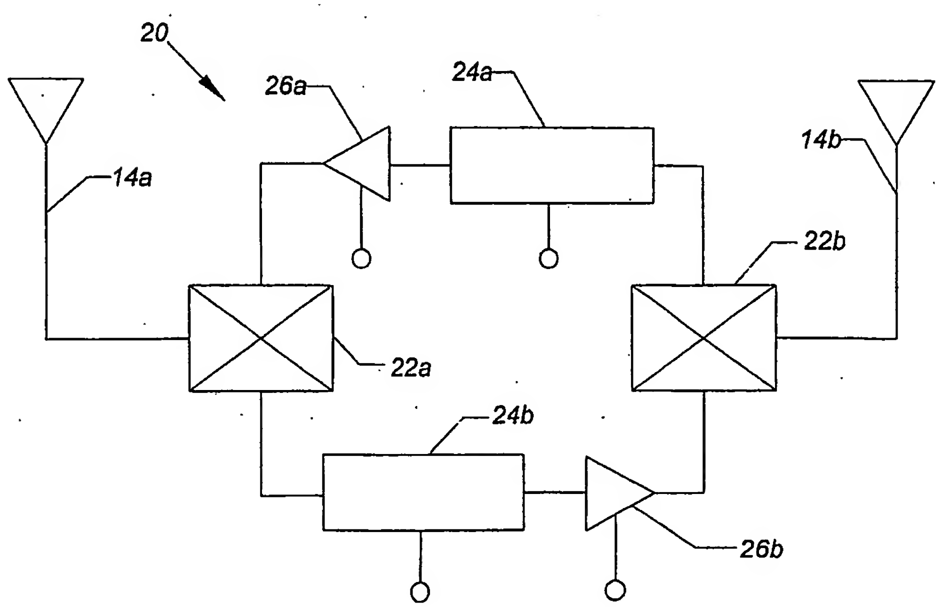


FIG. 2

INTERNATIONAL SEARCH REPORT

Internatio[redacted]Application No
PCT/US 02/31745

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04Q7/32 H04B7/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04Q H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	WO 02 28134 A (AEROSAT CORP) 4 April 2002 (2002-04-04) abstract page 3, line 9 -page 4, line 10 figure 1 claims	1,5,6
X	US 5 530 909 A (SIMON GEORGES-HENRI ET AL) 25 June 1996 (1996-06-25)	1,2,4-6, 12,13, 15,16
Y	the whole document	3,14
Y	DE 197 48 681 A (INNOTECH GMBH) 12 May 1999 (1999-05-12) abstract column 1, line 44 -column 2, line 7 column 4, line 65 -column 5, line 42	3,14

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 January 2003	24/01/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Dejonghe, O

INTERNATIONAL SEARCH REPORT

Internatio[redacted]Application No
PCT/US 02/31745

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO 89 04569 A (SUPERIOR ELECTRONIC DEV) 18 May 1989 (1989-05-18) figures 1,2	7-10 11
Y	WO 97 42720 A (GHASEMZADEH FARSHID ;JONSSON BO (SE); LG PRODUCTS AB (SE); ANDREAS) 13 November 1997 (1997-11-13) abstract page 1, line 12-18 figure 1	11
X	US 5 973 647 A (BARRETT MICHAEL J ET AL) 26 October 1999 (1999-10-26) column 3, line 52 -column 4, line 13	1,2,4-6
X	US 6 285 878 B1 (LAI JOSEPH) 4 September 2001 (2001-09-04) column 6, line 39-48 figure 7	7,8
X	DE 196 42 515 A (BOSCH GMBH ROBERT) 16 April 1998 (1998-04-16) the whole document	1,2,4-6, 12,13, 15,16

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Internatio[redacted]Application No
PCT/US 02/31745

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
WO 0228134	A	04-04-2002	AU	9313201 A	08-04-2002
			WO	0228134 A2	04-04-2002
US 5530909	A	25-06-1996	FR	2703537 A1	07-10-1994
			DE	69410333 D1	25-06-1998
			DE	69410333 T2	07-01-1999
			EP	0618704 A1	05-10-1994
DE 19748681	A	12-05-1999	DE	19748681 A1	12-05-1999
			AU	2048499 A	31-05-1999
			WO	9925135 A2	20-05-1999
WO 8904569	A	18-05-1989	AU	2628988 A	01-06-1989
			WO	8904569 A1	18-05-1989
			ES	2013813 A6	01-06-1990
			ZA	8808495 A	25-10-1989
WO 9742720	A	13-11-1997	SE	506571 C2	12-01-1998
			AT	228734 T	15-12-2002
			AU	2797997 A	26-11-1997
			DE	69717430 D1	09-01-2003
			EP	0894372 A1	03-02-1999
			SE	9601774 A	10-11-1997
			WO	9742720 A1	13-11-1997
US 5973647	A	26-10-1999	NONE		
US 6285878	B1	04-09-2001	NONE		
DE 19642515	A	16-04-1998	DE	19642515 A1	16-04-1998
			CZ	9901280 A3	15-09-1999
			WO	9817073 A2	23-04-1998
			EP	0932992 A2	04-08-1999
			PL	332605 A1	27-09-1999
			SK	47499 A3	14-08-2000

SHIPBOARD EXPERIMENTS FOR A MULTIHOP 802.11 COMMUNICATIONS SYSTEM– RF CHANNEL CHARACTERIZATION AND MAC PERFORMANCE MEASUREMENT

Thomas Bronez and James Marshall
The MITRE Corporation
McLean, VA

ABSTRACT

Wireless relays offer one approach to providing communications among small teams operating below-decks on neutral or hostile ships. Two sets of experiments were conducted aboard a container ship to determine the viability of this approach. In the first set of experiments, RF propagation loss and coherence bandwidth were assessed in both the 2.4 GHz and 5.8 GHz ISM bands. In the second set, packet latency and throughput were assessed for 802.11a and 802.11b networks operating in multihop configurations with hidden nodes. On the basis of these experiments, it is concluded that the wireless relay concept is workable in the shipboard environment using 802.11 wireless networks. The 802.11 variants offer different trades among data rate, relay separation, and supporting hardware requirements.

INTRODUCTION

Small teams operating below-decks on neutral or hostile ships face difficult communications due to the unreliable performance of conventional VHF/UHF handheld radios in shipboard environments. One approach to improving communications is to deploy wireless relays throughout the ship spaces as the team conducts its mission. This paper reports on experiments conducted aboard the container ship MV PAGE to determine the viability of the wireless relay concept[1].

Two types of experiments were conducted. In the first, RF channel characterizations were made in both the 2.4 GHz and 5.8 GHz ISM bands in two different ship spaces, using Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) transmission paths, to determine propagation loss and coherence bandwidth. In the second, the performance of 802.11a and 802.11b networks operating in multihop configurations with hidden nodes was measured in five different ship spaces to determine packet latency as a function of throughput.

In this paper, we describe both sets of experiments along with their results and draw conclusions about the viability of the wireless relay concept.

[1] These experiments were funded by the Internal Research & Development program of the MITRE Center for Enterprise Modernization.

RF CHANNEL CHARACTERIZATION

Objective and Approach

The objective of these experiments was to characterize the 2.4 GHz and 5.8 GHz shipboard radio propagation channels in support of COTS 802.11 component selection for implementing the wireless relay communications concept.

Data was collected using a sweep generator and a spectrum analyzer as shown in Figure 1. The generator frequency was slowly moved across the band of interest and the received signal level measured on the spectrum analyzer in peak-hold mode with a 300 KHz resolution bandwidth. The accumulated incoherent frequency-domain channel response was transferred to a PC for storage. Low-gain, omni-directional antennas were used for transmit and receive to avoid selectively capturing multipath components. We conducted separate tests with both antennas oriented in the vertical polarization, both in the horizontal polarization, and with one vertical and one horizontal.

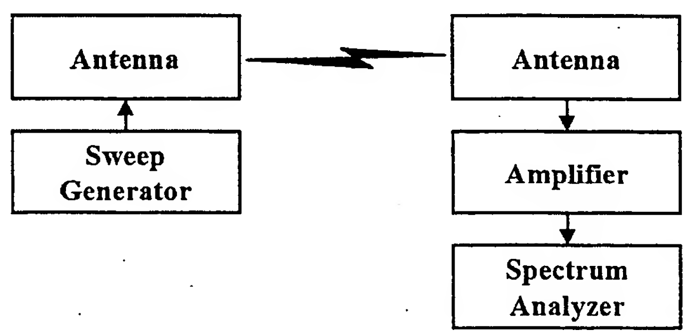


Figure 1. RF Channel Characterization Setup

In our post-collection data analysis, propagation losses were computed by comparing the received power level with the transmitted power level across the entire band. Coherence bandwidth was estimated by autocorrelation of the measured power spectrum as follows. The measurements, expressed in dBm, consisted of about 600 data points and covered a frequency span of 100 MHz; hence the data points are approximately 167 kHz apart in frequency. First, the data points were converted from a power level in dBm, to a normalized amplitude representa-

tion. Then the data was broken into overlapping blocks of 8.333 MHz width and 4.1667 MHz overlap; each of these blocks contained 50 points. An inverse FFT was performed on each of these blocks to change to the time-domain. We then computed the magnitude squared of each time-domain block, averaged the result across all the blocks, and transformed back to the frequency domain. This produced a frequency-domain correlation plot, covering positive frequencies, that allows us to approximate the coherence bandwidth of the channel. We consider the half-power point on the plot, and double the resulting frequency noted at this half-power point to get the two-sided coherence bandwidth estimate. These values are provided in Tables 4 and 8 below.

Engine Room Experiments

The engine room on the ship was a very large room containing the main engine, catwalks, air ducts, tools, plumbing, and other large pieces of equipment. The engine room had about eight levels and was roughly 55 feet wide, 70 feet long, and 70 feet high. We placed the receive end of our test equipment near the middle of the engine room on the port side. The experiment was run with the transmit end in five different locations as described in Table 1.

Tables 2 and 3 respectively show the propagation losses in the 2.4 GHz and 5.8 GHz bands. From this data, we see that polarization did not make much difference. However, the 5.8 GHz signal ended up about 10 dB lower than the 2.4 GHz signal. Distances were not measured since their relevance is unclear in this propagation environment. However, in a general sense, the loss increased with increasing separation between the transmitter and receiver; see the trend from location A to B to C to D. Additionally, blockage increased loss; compare locations C and E, which are separated by the engine. Cavities behaved similarly; compare location B, in a side room, with A, as well as location D, down the shaft tunnel, with C.

Table 4 shows the estimated coherence bandwidth for both bands. At 2.4 GHz, the coherence bandwidth tends to decrease as the locations become more challenging. The 5.8 GHz channels exhibit more consistency among the locations, including the line-of-site test to location A, and have somewhat larger coherence bandwidths.

Table 1. Engine Room Transmitter Locations

Location	Description
A	Port side of the engine room, about 50 feet forward of the receiver (line-of-sight)
B	Small room 10 feet off to the side of location A through opening (non-line-of-sight)
C	Lowest level of engine room, port side, 4 levels below the receiver (non-line-of-sight)
D	Shaft area of the engine room, about 45 feet aft of location C (non-line-of-sight)
E	Lowest level of the engine room, starboard side, 4 levels below the receiver (non-line-of-sight). The bottom of the engine separated locations C and E.

Table 2. Engine Room Loss at 2.4 GHz

Location	Signal Level (dBm)			Loss rel. to A
	V	H	X	V/H Ave.
A	-15.2	-15.7	N/A	0.0
B	-20.7	-22.2	-22.0	-6.0
C	-29.4	-30.0	-29.8	-14.3
D	-35.9	-36.8	-35.4	-20.9
E	-35.0	-35.8	-35.8	-20.0

Polarization: V = vertical, H = horizontal, X = cross

Table 3. Engine Room Loss at 5.8 GHz

Location	Signal Level (dBm)			Loss rel. to A
	V	H	X	V/H Ave.
A	-27.8	-26.3	N/A	0.0
B	-31.3	-31.2	-30.5	-4.2
C	-40.0	-40.1	-40.2	-13.0
D	-45.9	-44.9	-45.7	-18.3
E	-45.0	-45.9	-45.6	-18.4

Table 4. Engine Room Coherence Bandwidth

Location	Coherence BW (MHz) at 2.4 GHz			Coherence BW (MHz) at 5.8 GHz		
	V	H	X	V	H	X
A	2.4	2.0	N/A	3.0	2.0	N/A
B	2.0	2.2	N/A	3.0	3.0	N/A
C	2.0	2.4	1.6	N/A	N/A	2.2
D	2.2	1.8	2.0	2.4	2.4	3.0
E	1.4	1.6	1.6	2.4	2.4	2.0

Corridor Experiments

In a second set of experiments, the channel of the port access corridor was characterized; this corridor runs along the port side of the ship from the fan tail to the bow section for a total length of about 800 feet. As with the engine room experiments, the receive end was placed at a fixed location and the transmit end was positioned at various locations along the corridor for different tests. The receiver was about 35 feet forward of the aft bulkhead door leading to the fantail at the stern of the ship. The experiment was attempted with the transmit end in five different locations as described in Table 5.

Tables 6 and 7 show propagation losses in the 2.4 GHz and 5.8 GHz bands, respectively. We see again that polarization did not make a great deal of difference. The 5.8 GHz signal was weaker, this time by an average of about 8 dB. We also see that having a person between the transmitter and receiver causes a loss of about 1 or 2 dB.

It is instructive to examine the dependence of this data on distance. Neither a logarithmic dependence (e.g., a free space model) nor a linear dependence (e.g., a waveguide model) on distance is perfect. For the 2.4 GHz band, a logarithmic model yields a signal level falling about 50 dB/decade of distance, while a linear model yields a loss of about 0.15 dB per foot. For the 5.8 GHz band, a logarithmic model yields a signal level falling about 40 dB/decade of distance, while a linear model yields a loss of about 0.12 dB per foot.

Coherence bandwidths were difficult to measure from the corridor data due to insufficient signal levels or occasional interference. However, some results for the first two locations are shown in Table 8. The 5.8 GHz band again exhibits a somewhat larger coherence bandwidth than the 2.4 GHz band.

Summary of RF Channel Characterization

In summary, we have learned a number of things from the test results. First, we see that in both sets of tests, polarization did not have a great deal of impact on signal levels. This was even true when the polarizations were crossed. This is probably due to the high amounts of multipath reflections that likely change the signal polarization.

Second, we see is that frequency does indeed make a difference. We see a difference of 8 or 10 dB between the 2.4 GHz results and the 5.8 GHz results, the higher frequency having a lower received power. This should not be surprising, since calculations for signal loss in free space tell us to expect an additional 7.7 dB of loss at 5.8 GHz relative to 2.4 GHz.

Table 5. Corridor Transmitter Locations

Location	Description
A	60 feet forward of the receiver, just before a large green electrical box obstructing much of the corridor (line-of-sight). For one test, a person stood in the corridor between the transmitter and the receiver.
B	192 feet forward of the receiver, well past the electrical box mentioned in A, but not past a second electrical box about 243 feet from the receiver (partial line-of-sight– the receiver could be seen were one standing in the correct position)
C	432 feet forward of the receiver, well past the second electrical box mentioned in B (theoretically line-of-sight, but very difficult to see the receiver due to small subtended angle). No data was collected at this location, since the signal was too weak.
D	337 feet forward of the receiver, past the second electrical box mentioned in B (theoretically line-of-sight, but somewhat difficult to see the receiver due to small subtended angle)

Table 6. Corridor Loss at 2.4 GHz

Location	**Signal Level (dBm)**			**Loss rel. to A**
	V	**H**	**X**	**V/H Ave.**
A	-15.9	-17.6	-16.1	0.0
B	-40.9	-39.6	-42.1	-23.5
D	-56.6	-54.9	-56.7	-39.0
A-P[1]	-16.8	-17.6	N/A	-0.4

[1] A person stood between the transmitter and the receiver.

Table 7. Corridor Loss at 5.8 GHz

Location	**Signal Level (dBm)**			**Loss rel. to A**
	V	**H**	**X**	**V/H Ave.**
A	-27.5	-27.2	-27.9	0.0
B	-48.6	-43.9	-46.2	-18.9
D	-60.1	-59.3	-56.7	-32.4
A-P	-28.8	-29.0	-29.3	-1.6

Table 8. Corridor Coherence Bandwidth

Location	**Coherence BW (MHz) at 2.4 GHz**			**Coherence BW (MHz) at 5.8 GHz**		
	V	**H**	**X**	**V**	**H**	**X**
A	2.0	1.6	2.2	3.6	2.8	2.2
B	2.4	1.8	1.6	N/A	3.0	N/A

Third, multipath is relatively severe. This is characterized in terms of the coherence bandwidth. For the tests considered in this report, the coherence bandwidth is on the order of 2 MHz, but varies between about 1.5 and 3.6 MHz. This does not seem to be wide enough to successfully pass the large bandwidth of the direct sequence spread spectrum (DSSS) version of 802.11b (DSSS version of IEEE 802.11b is approximately 11 MHz wide). However, equalization would improve performance of the 802.11b waveform.

In the propagation tests in the hallway, we measured the impact on signal level by having a person in the transmission path partially blocking the signal's LOS. This did not seem to have a large effect, but degraded signal levels by about 1 dB in our tests.

In the hallway tests we also measured signal loss as a function of distance. In these tests, we learned that the signal loss was less than that in free space for short path distances, but it fell off at a rate greater than the inverse of distance squared (r^2). Having a received signal stronger than what would be predicted by free space loss calculations is probably due to the waveguide effects of the hallway. The greater slope is probably due to the high loss nature of this waveguide. By the time the distance got to about 400 feet, the path loss was about the same as for free space. For distances less than about 400 feet, we would expect 802.11b data transmission to be very good. To the extent that this was not the case, it was probably because the coherence bandwidth was not sufficient for the waveform bandwidth.

In conclusion, we can make some observations about which systems are likely to work the best. Clearly systems with higher power have a distinct advantage. Beyond that we expect that systems operating at 2.4 GHz (802.11b and 802.11g) will perform better than those at 5.8 GHz (802.11a) due to signal loss considerations. We also expect that the orthogonal frequency division multiplex (OFDM) waveform (802.11a and 802.11g) will be advantageous relative to the DSSS waveform (802.11b), since the instantaneous bandwidth of the OFDM signal is much smaller. This is due to the coherence bandwidth limitations of the channel. Hence, 802.11g would seem the best waveform, given that power levels and all other things were equal. However, additional practical considerations may drive the waveform decision toward other solutions.

MULTIHOP RELAY ASSESSMENT

Objective and Approach

The objective of the Multihop Relay Assessment experiments was to evaluate the throughput and latency of 802.11a and 802.11b wireless networks in a shipboard multihop configuration with hidden nodes. Hidden nodes occur in wireless environments for which two nodes are out of range of each other yet within range of a common third node. To avoid collisions at the third node, the 802.11 Media Access Control (MAC) protocol supports Request to Send/Clear to Send (RTS/CTS) operation as part of its Distributed Coordination Function (DCF). However, the DCF is inefficient in multihop configurations and operates with reduced throughput and increased latency relative to configurations free of hidden nodes [1, 2].

Throughput, measured in kilobits per second (Kbps), is important with respect to the total traffic that can be supported by the system. For example, voice encoded with the GSM 6.10 codec requires about 15 Kbps. Transmission of a 100 kilobyte jpeg-encoded image in 10 seconds requires 80 Kbps. Moderate frame-rate, low-resolution color video typically requires about 256 Kbps.

Latency, measured in seconds, is critical to voice traffic in the system. Push-to-talk, half-duplex voice communications become increasingly unwieldy as the total latency (including both network and client delays) grows beyond 0.5 seconds. Longer latencies are typically acceptable for file transfers.

The testing approach established a chain topology of test nodes with static two-way routes connecting the start and the end of the chain; static routing eliminated the need for any routing control traffic on the network. For each test, a controlled sequence of packets was sent along the chain from the first node to the last node, which then reflected the packets back to the first node along the reverse route. Packet size and transmission rate were controlled to achieve specific throughput. Timestamps were employed to measure the round-trip latency of each delivered packet and to detect missing packets. The measured latency encompasses media access contention, forwarding delays within intermediate nodes, and reflection delays within the end node.

We employed a chain of four nodes, yielding a maximum round-trip route of six hops. For 802.11a experiments, each node was a Pentium III laptop running Windows XP and hosting a 60 mW Proxim 802.11a/b/g wireless network interface, model 8480-WD. For 802.11b experiments, the first node was a Pentium III laptop running Windows XP and hosting a 100 mW Cisco 802.11b wireless network interface, model Air-PCM352, while the remaining three nodes were ARM PXA255 embedded com-

puters running Windows CE 4.2 and hosting the same model Cisco wireless network interface.

Bow Section 802.11a Experiments

We measured the performance of the 802.11a network in the bow section of the ship. The configurations and results of the experiments are shown in Figure 2. The bow section is a compact area containing several decks with offset openings for access between decks. Propagation was surprisingly good, even in NLOS conditions. Therefore, we could not separate the nodes far enough apart to achieve the 6 hop round-trip configuration described in the baseline test procedure. The results indicate very good network performance; latencies were no longer than 0.15 seconds even at a throughput of 512 Kbps.

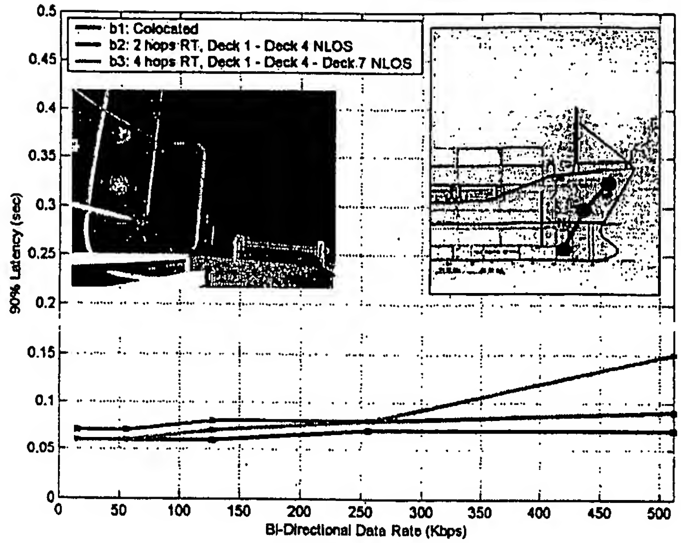


Figure 2. Bow Section 802.11A Experiments

Starboard Tunnel 802.11a Experiments

We measured the performance of the 802.11a network in the starboard access tunnel of the ship. The configurations and results of the experiments are shown in Figure 3. Note that the most-forward link, reaching from the end of the tunnel into the bow section, was NLOS and shorter than the other links. At high throughputs (512 Kbps), we observed poor performance (significant packet loss despite low latency of delivered packets) when hidden nodes were present ("4 hop" and "6 hop" configurations). However, lower throughputs exhibited both low packet loss and low latency.

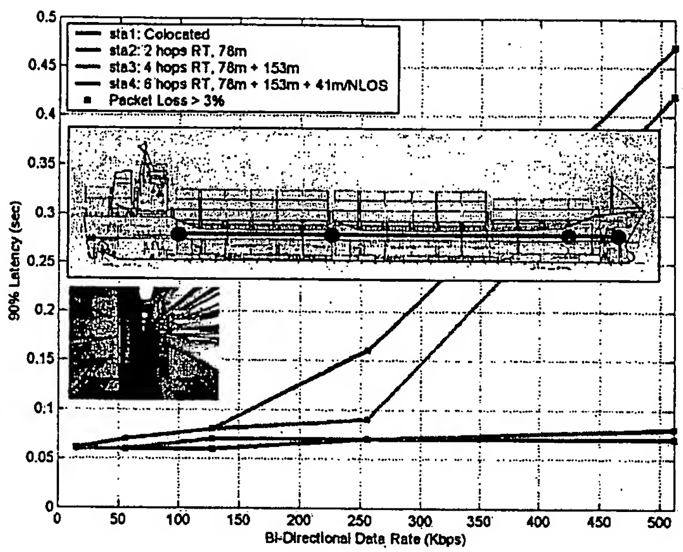


Figure 3. Starboard Tunnel 802.11a Experiments

Starboard Tunnel 802.11b Experiments

We measured the performance of the 802.11b network in the starboard access tunnel of the ship. The configurations and results of the experiments are shown in Figure 4. As with the starboard tunnel 802.11a experiments, the most-forward link was NLOS and shorter than the other links. At high throughputs (512 Kbps), we observed poor performance (significant packet latency despite little packet loss) when hidden nodes were present ("4 hop" and "6 hop" configurations). However, lower speeds exhibited negligible packet loss and latency sufficient to support voice. A slightly shorter "4 hop" configuration showed good performance even at high speeds.

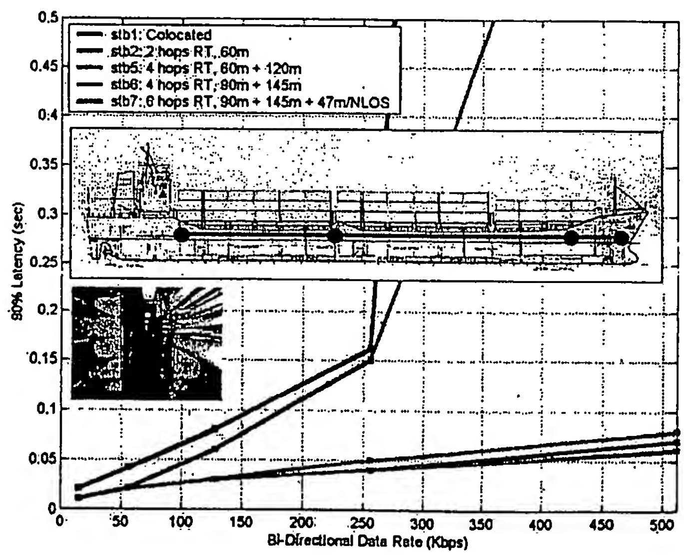


Figure 4. Starboard Tunnel 802.11b Experiments

Engine Room 802.11b Experiments

We measured the performance of the 802.11b network in the engine room of the ship. The engine room is a large, fairly open volume encompassing multiple decks. Upper decks consist of catwalks running around the walls of the room; flooring of lower decks is a mix of irregular grates and metal panels fit around large pieces of equipment. One node was fastened at the corner railing of Deck 2; the remaining nodes were moved around the engine room. The configurations and results of the experiments are shown in Figure 5. The configuration dimensions are sufficiently large that a large multipath delay spread is likely.

In the first experiment, a remote node was placed diagonally across the room on the far corner of the catwalk. In subsequent experiments, the remote node was placed on lower decks without LOS to Node 4. Propagation was surprisingly good in these NLOS conditions. Therefore, we could not place additional nodes far enough apart to achieve any hidden-node configurations; the first node was in radio range from all points in the engine room. Therefore, we simply moved the remote node around the room to various locations. The results indicate very good network performance, achieving latencies no longer than 0.15 seconds for throughputs of 256 Kbps and slower. No lost packets were encountered. We conclude the multipath delay spread was within limits of the wireless interface[2]. Given that the links worked, the network was well-behaved since there were no hidden nodes.

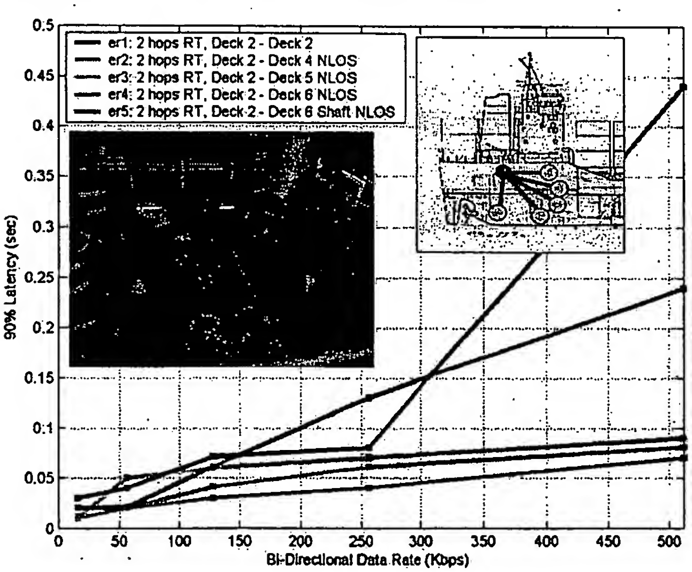


Figure 5. Engine Room Throughput-Latency Experiments with Cisco 802.11b Radios

Exfiltration 802.11b Experiments

We measured the performance of the 802.11b network in an exfiltration configuration from the interior engine room to the exterior stern of the ship. The configurations and results of the experiments are shown in Figure 6. One node was fastened at a central railing along a catwalk on Deck 2 of the engine room, but with LOS to a hatch exiting to the starboard tunnel. A second node was placed in the starboard tunnel 1 m outside the closed hatch from the engine room, and several meters from the end of the tunnel with its hatch exiting to the fantail. A third node was placed in the fantail 2 m outside the closed hatch from the starboard tunnel. Finally, a fourth node was placed in one of two locations without LOS to the third node. One location was around a corner on the port side of the fantail; the other location was one deck above on the starboard side of the fantail.

All in all, these were very challenging configurations in that no two nodes had LOS to each other. The first configuration performed somewhat better than the second; in the latter case, insufficient packets were delivered at 512 Kbps to run the test. As might be expected, latencies generally worsened rapidly with throughput in these experiments. We suspect that poor signal quality compounded hidden node issues. Yet, total latency was no more than 0.2 seconds at a throughput of 128 Kbps for both configurations.

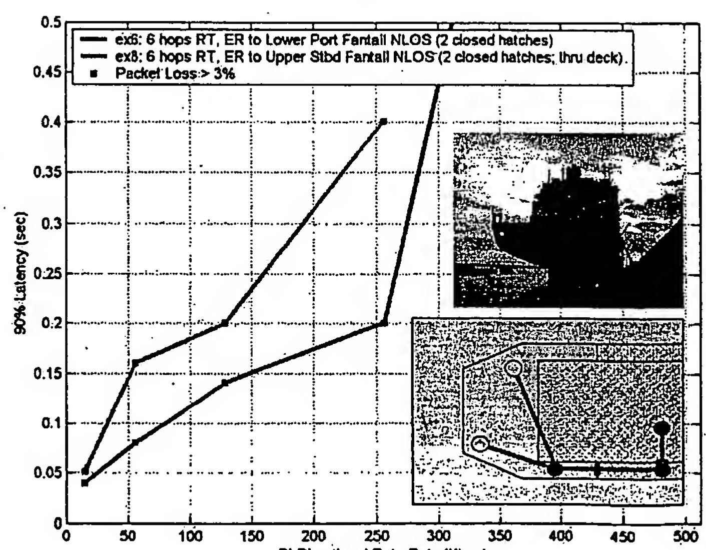


Figure 6. Exfiltration Throughput-Latency Experiments with Cisco 802.11b Radios

[2] Cisco advertises good performance for delay spread below 500 nanoseconds, or a maximum differential path length of about 500 feet.

Summary of Multihop Relay Assessment

Several conclusions may be drawn from our analysis of the measured data. First, it appears that both 802.11a and 802.11b wireless networks are workable in the shipboard environment. Our measurements indicated that 802.11a offers more multipath resistance than 802.11b, while 802.11b generally offers smaller propagation loss, less expensive network hardware, and less expensive host hardware than 802.11a. We observed that under network congestion, the Proxim 802.11a radios drop packets in order to lower the latency of delivered packets. Conversely, the Cisco 802.11b radios allow packets to build up within the network at ever-increasing latency while delivering almost all packets (presumably until network buffers fill).

Second, multipath conditions on the ship were not debilitating; instead, propagation loss was the primary limitation in separating nodes. Therefore, 802.11b is the preferred network interface for wireless communications so long as data rates are sufficiently low. Our results indicate that a handful of voice-quality channels of 15 Kbps each can be supported simultaneously in most locations on the ship. Higher-throughput communications can be conducted with higher latency. However, one should not expect to achieve the highest data rates of the 802.11 specifications, because the hidden nodes and RTS/CTS handshaking of the 802.11 DCF greatly impact overall throughput.

Third, communications over much of the ship appears feasible with a series of deployed wireless relays. Such a network could be constructed as follows with 7 nodes:

1. Rear of fantail
2. On side of fantail, just outside starboard tunnel hatch
3. Within starboard tunnel, just outside engine room hatch
4. Within engine room, on Deck 2
5. Within starboard tunnel, midway along length
6. Within starboard tunnel, near bow
7. Within bow, level with tunnel, at opening to lower decks

Additional relays would be useful to fill in, for example, along the top of the main deck or down the port tunnel.

CONCLUSIONS

RF channel characterizations were made in both the 2.4 GHz and 5.8 GHz ISM bands in two different ship spaces using line-of-sight and non-line-of-sight transmission paths. Propagation loss was approximately independent of polarization. In a long corridor, loss was smaller than that of free space, but greater than that of a waveguide. Coherence bandwidths were estimated.

The performance of 802.11a and 802.11b networks operating in multihop configurations with hidden nodes was measured in several different ship spaces. Packet latency as a function of throughput depended strongly on the number of hidden nodes, but was generally under 100 msec for bi-directional throughputs of no more than a few hundred kilobits per second. Even in the most severe configuration (an exfiltration test involving two hops through closed hatches and one hop through a deck), latencies at data rates commensurate with compressed speech were sufficiently small to support reliable voice communications.

On the basis of these experiments, it is concluded that the wireless relay concept is workable in the shipboard environment using 802.11 wireless networks. Propagation loss and multipath delay spread favor 802.11g for high data rate systems. However, some 802.11b implementations are acceptable for communications at voice data rates and may be favored because of other issues, such as device bus requirements.

REFERENCES

[1] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks?" *IEEE Communications Magazine*, vol. 39, no. 6, June 2001, pp. 130-137.

[2] Hou, et al, "Analyzing the Throughput of IEEE 802.11 DCF Scheme with Hidden Nodes," *IEEE 2003 Vehicular Technology Conference*, vol. 5, October 2003, pp. 2870 - 2874